

VII-1. Failure of Radial (Tainter) Gates under Normal Operational Conditions

Radial Gate Arrangement

Introduction

Radial gates (sometimes referred to as Tainter gates) consist of a cylindrical skinplate reinforced by vertical or horizontal support ribs, horizontal or vertical girders, and the radial arm struts that transfer the hydraulic loads to the gate trunnions. Radial gates rotate about their horizontal axis during opening/ closing operations. This chapter addresses potential failure modes related to radial gates during normal operational conditions. This includes operation of spillway gates during floods, where spillway gates are operated with the reservoir water surface below the top of the gates, operation of the spillway gates to pass normal flows (possibly as a result of powerplant being down for maintenance), and exercising of the gate during periodic gate inspections. It does not specifically address operation of spillway gates with the reservoir water surface above the top of the gates (although spillway gate overtopping conditions should be considered if it has a reasonable chance of occurrence). This chapter also does not address potential failure modes for radial gates at navigation dams initiated by barge traffic (impact loads from barges, etc.). These potential failure modes are addressed in Chapter VIII-1.

In general, two types of radial gates can be identified at dams: spillway crest gates (ref to **Figure VII-1-1**) and top sealing gates. Crest radial gates are designed for the reservoir level up to the top of the skinplate; however, some of the gates have been designed for overtopping flow conditions. Top sealing radial gates are submerged and can take the load corresponding to several hundred feet of water head. Radial gates come in all sizes from only a few feet wide up to 110-feet (or even wider) for navigation structures. Similarly, the height of the gate may reach 50 feet or even more. Radial gates are operated by hydraulic cylinders or by wire ropes or chain winches (ref. **Figure VII-1-1**).



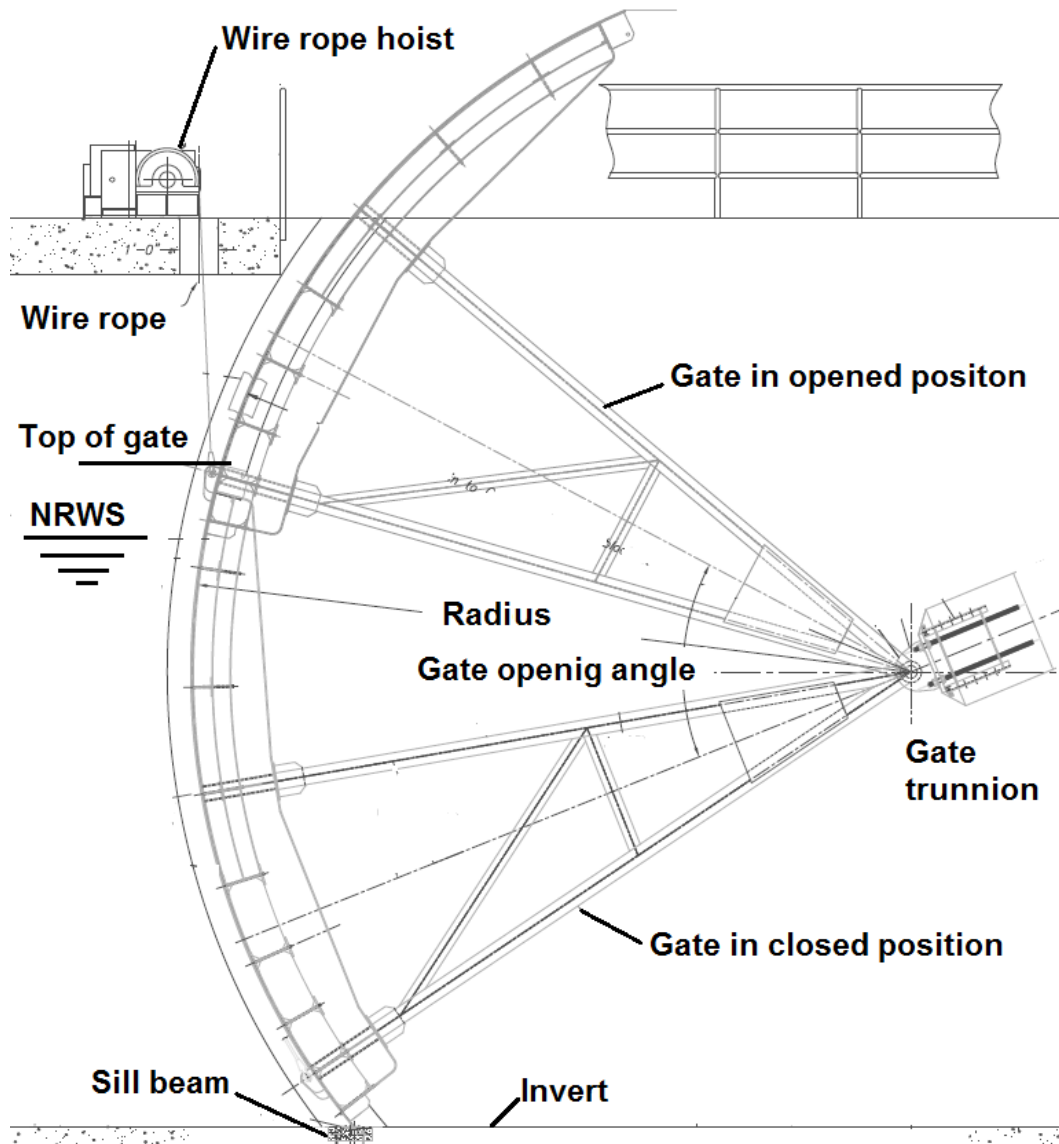


Figure VII-1-1 – Arrangement of a typical radial gate operated by the wire rope hoist.

Load Conditions for Radial Gates

In the structural analysis of radial gates, three critical operation conditions are considered:

Gate closed with the load combination of hydrostatic load, self-weight of the gate, weight of installed equipment, ice load, wave action, and debris.

The hydrostatic pressure from the reservoir is the primary load acting on the gate. The reservoir load, together with the wave action, and the weight of the gate and installed equipment is considered as a normal load. The ice and debris loads are unusual loads. Impacts from barges, boats and debris are extreme loads (these conditions are addressed in Chapter VIII-1).

A specific arrangement of the gate geometry and imperfections of gate arms may introduce second order forces in the gate structure that lead to:

- i. *Out-of-plane bending of arm struts* – deformation of gate girders may bend the arm struts in the out-of-arm frame plane. The eccentricity will be magnified by the compression forces in the arm struts increasing the bending moment of the struts. The second order bending moment will be increased for an arm strut with large imperfections.
- ii. *In-plane bending of arm struts* – imperfections in the assembly of the gate structure together with deflection of the arm struts caused by the self-weight may result in eccentricities of the arm struts. These eccentricities will lead to increased second order bending moment in the struts due to the axial compressive load from the reservoir.

Gate operated with the load combination of hydrostatic load, self-weight of the gate, weight of installed equipment, loads from the gate hoists, trunnion pin friction, side seal friction, flow-induced hydrodynamic loads, and wind load.

Whenever radial gates are operated, friction forces develop at the interface between the trunnion pin and the bushing and between the trunnion hub and the side yoke plate. The friction load acts in a direction opposite to the motion of the gate. The friction moment at the gate trunnion is a function of the trunnion reaction force acting normal to the face of the pin, the radius of the pin, and the coefficient of friction between the pin and the bushing. The peak of the trunnion resistance occurs as the movement at the pin/bushing interface begins to break free through its static friction into dynamic frictional resistance. The maximum moment can be expected to occur when the gate is loaded under full head, the gate has remained in the closed position, and starts to open to regulate the reservoir level.

During operation of radial gates, the hydrostatic load together with the bending moment at the gate trunnion caused by pin friction, remain the primary loads on the gate. As operation of the gate is initiated, the hoist loads and the trunnion pin friction loads are mobilized, magnifying bending of the gate arms when compared with the "Gate Closed" conditions. The increased bending of the arm struts during operation and related second-order forces in the struts, may significantly affect the stability of the gate due to overstressing both the struts and bracing of the gate arms.

This chapter addresses the potential failure mode of radial gates during normal gate operation. This could either be during a flood situation, where spillway releases are needed to pass inflows (and potentially avoid a significant increase in the reservoir water surface elevation that could approach the dam crest elevation) or during non-flood operations. Non-flood operation of spillway gate could be associated with routine exercising of the gates or with passage of normal releases through the spillway when other waterways (power penstocks or outlet works) are not available.

Earthquake load conditions are discussed in Chapter II-3 of the Best Practice Manual.

Failure Mechanisms of Radial Gates

Spillway radial gates transfer the reservoir load to the trunnion pin through compression of the gate arms (see Figure **VII-1-1**). Spillway radial gates are most vulnerable to failure when they are initially opened, with the hydrostatic load on the gate combined with the maximum hoist load and trunnion friction.

Trunnion pin friction needs to be considered when analyzing a radial gate during operation. An increase in pin frictional moment will increase the combined arm stresses, which can lead to a greater probability of arm strut buckling failure or overstressing of the bracing leading to an increase in unsupported length of the strut arms. This potential failure mode will only apply when the spillway gates are operated and frictional resistance is developed at the gate trunnion.

Other factors that contribute to the potential for radial gates failure include:

Corrosion of the critical gate members and their connections

Overtopping the gate during flood events

Significant spillway pier deformation

Improper modifications to gate structure (gate height rising, welded new components etc.)

Ice forming on the gate structure

Uneven lifting loads

Fatigue of structural gate members

Factors Influencing Safety/Stability of Radial Gates

Assembly of Gate Trunnion

The frictional moment at the gate trunnion is a function of the total reaction of loads carried into the gate trunnions, the pin diameter, the coefficient of friction between the pin and the bushing, and friction between the face of the trunnion hub and the trunnion yoke face.

i. Size and type of trunnion pins – the majority of radial gates are equipped with solid trunnion pins vs. hollow pins. The diameter of solid pins varies from a few inches (for small gates) up to 18 inches for large radial gates. Hollow pins result in larger outside diameters (32 inch hollow pin was installed at the Folsom Dam spillway radial gates) that may lead to higher frictional moments at the gate trunnion and higher bending moment in the gate arms.

ii. Type of trunnion pin material – in the modern design of radial gates, stainless steel is generally specified for trunnion pin material. This prevents corrosion of the pin and consequently does not lead to an increase in the coefficient of friction during the life of the gate, unless the pin bushing fails. However, some of the radial gates, including the spillway gates at Folsom Dam, are equipped with a carbon-steel type pins.

ii. Friction at sides of trunnion hub – lateral trunnion reaction (force parallel to the axis of gate trunnions) may generate friction between arm hubs and the trunnion yoke as the gate is operated. The frictional resistance will contribute significantly to an increased bending moment of the gate arms.

iii. Type of trunnion bushings – Over the years, various types of bushings in radial gate trunnion assemblies have been utilized. In some old and small radial gates, the gate trunnion assembly is comprised of a small steel pin passing through an oversized hole of a carbon steel plate (used as a hub) without the presence of any bushing. In the current practice, the radial gate trunnion assembly is generally equipped with self-lubricating or grease lubricating bushings that rotate around stainless steel pins. Several types of trunnion bushing arrangements can be identified for radial gates.

Plain Bronze Bushings - Plain bronze cylindrical bushings bear on steel trunnion pins.

Externally Lubricated Bushings – Bronze bushings are lubricated by injecting grease into the pin/bushing interface. In some instances, the injection point provides an inadequate single point of lubrication. In major gate installations, the inner surface of the bronze bushing has been machined with grease grooves to allow a better and more even distribution of lubrication. Lubrication at the trunnion pin is critical to maintain low friction of the gate trunnion. If lubrication is not maintained, friction between the pin and the bushing will increase over time.

Graphite-Insert Self-lubricating Bushings – In the latter half of the 1940s, the bearing industry had developed self-lubricating journal bearings. However, the lubricant used for the bushings was a graphite plug that was inserted into recesses on the inside of the bronze bushing. The graphite proved to be a bad choice for hydraulic applications because it is known to cause galvanic corrosion and pitting of stainless and carbon steel leading to an increased coefficient of friction and greater pin frictional moment .

Self-Lubricating Bushings – Self-lubricating bushings are bushings that do not require the regular application of external lubricant. There are a number of different types and manufacturers of self-lubricating bushings. All of them include solid lubricants, which provide a low coefficient of friction. Examples of self-lubricated bushings include a solid lubricant embedded in a bronze or stainless steel backing or a composite material which incorporates woven fabric reinforcement and solid lubricants within a resin matrix. In the 1970s, Reclamation began specifying self-lubricating bushings that utilized proprietary lubricants formulated without the addition of graphite or molybdenum, however, composite bushings have not been implemented on any Reclamation projects.

It has been recognized that self-lubricating bushings (that do not contain dissimilar metals) are the most reliable design, followed by a plain bronze bushing and then lubricated bushings. Graphite inserts have been found to be the least desirable design due to their vulnerability to corrosion.

Coefficient of Friction for Different Pin Bushing Arrangements

Table VII-1-1 provides typical values of trunnion pin friction for the as-designed condition.

Table VII-1-1

Typical Pin Friction Values for Different Pin-Bushing Arrangements (As-Designed Conditions)	
Pin-Bushing Arrangement	Typical Friction Coefficients
Steel Pin on Steel Plate	0.4 - 0.8
Plain Bronze Bushings on Steel Pin	0.3
Externally Lubricated Bushings on steel pin	0.1 – 0.2
Self-Lubricating Bushings	as specified by the bushing manufacturer
Graphite Insert Self-Lubricated Bushings	0.1

Failure of Bushings

A failed bushing represents a state in which the bushing does not meet the original design intent. This can involve loss of some of the lubricant material for self-lubricating bushings, non-existent or ineffective lubricant for externally lubricated bushings, or a cracking of the bushing shell. Failure of bushings will most likely result in an increase in trunnion pin friction. Typical values of pin friction for failed bushings are provided in **Table VII-1-2**.

Table VII-1-2

Typical Pin Friction Values for Different Pin-Bushing Arrangements (Failed Bushings)	
Pin Bushing Arrangement	Typical Pin Friction Coefficients
Externally Lubricated Bushings	0.3
Self-Lubricating Bushings	0.3
Graphite Insert Self-Lubricated Bushings	0.3

Maintenance of Spillway Gates

Gates that are well maintained and periodically exercised can usually be relied upon to have their original design capacity at the time they are operated, although many gates were not designed in the past to meet current design requirements. Key maintenance items are:

Lubrication of the trunnion pin – Externally lubricated bushings and self-lubricating bushings rely on a lubricant to reduce trunnion pin friction. Maintenance practices at the dam can lead to an increased or decreased reliability of lubrication to reduce trunnion pin friction. If the gates with externally lubricating bushings are lubricated through just one port and are then not exercised through their full range to ensure the entire pin is lubricated, there may not be a significant reduction in friction.

Self-lubricating or graphite bearings - The condition of these should be evaluated and the trunnion friction determined periodically to ensure they continue to perform as intended. There are several different methods that can be used to calculate trunnion friction and methods that are used should be chosen after careful consideration. This would only be done once it has been determined that the radial gates pose a risk to the project and downstream population.

Periodic inspection will allow identification and maintenance of any damage and corrosion of gate members, and preserve the original design capacity of the gate.

Regular gate exercise helps to ensure that the trunnion bearings are not bonded and the gate can operate smoothly and is performing as expected. Exercising of the gates will verify that the gate can travel freely within the gate bay, at least for smaller gate openings.

Wire rope and chain inspection and lubrication – corrosion of the chains and uneven tensioning of wire ropes can lead to unsymmetrical lifting loads, increasing the loads on one side of the gate and introducing torsional loads.

Hoist Ropes and Chains/Gate Binding

Some other mechanisms that may lead to failed gate operation include failure of hoist wire ropes or hoist chains and gate binding. While these mechanisms may not lead directly to gate failure and an uncontrolled release of the reservoir, they could result in inoperable gates during a large flood. They could initiate gate overtopping and increased loading or overtopping of the dam. The flow over the gate skin plate will result in additional load on gate arms leading to potential failure of the gate. If gates are well maintained, the chance of an inoperable spillway gate during a large flood will be significantly reduced. Inspections of the gates should focus on wear or corrosion of wire ropes and chains and connections of the ropes and chains to the gates and the hoists.

Fatigue of Arm Members

Opening and closing operation of the gate may lead to low-cyclic fatigue failure of the gate members or their connections. Stability of the radial gates relies on the strength of members and their connections.

In general, the gate arm members and connections subject to typical cyclic loading during gate operations will not create fatigue conditions if the developed stress range is within the limit of the static allowable stress. Excessive vibration of the gate during operation can lead to increased cycles leading to fatigue cracking. For stresses exceeding the design limits, a fatigue analysis needs to be considered.

Failure of Radial Gate at Folsom Dam - Relevant Case History

Introduction

One of eight large spillway radial gates failed at Folsom Dam in California during reservoir releases on July 17, 1995. The gate failure occurred with a nearly full reservoir releasing a peak flow of about 40,000 ft³/s (the rated downstream safe channel capacity was 115,000 ft³/s). No injuries or fatalities occurred as a result of the gate failure.

Folsom Dam was designed and constructed by the U.S. Army Corps of Engineers between 1948 and 1956. The dam was transferred to the Bureau of Reclamation for operation and maintenance in 1956. The dam consists of a concrete gravity section across the river channel flanked by long earth fill wing dams. The concrete dam has a gated

overflow spillway section that is regulated by eight tainter (radial) gates: five service gates and three emergency gates.

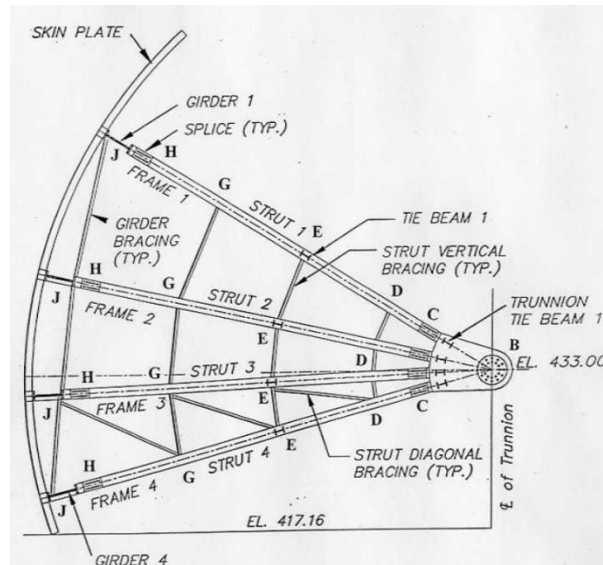


Figure VII-1-2 – Radial Gate Arrangement at Folsom Dam

Description of the incident

Gate No. 3 was being operated at approximately 8 a.m. on July 17, 1995 to maintain flow in the river during a powerplant shutdown. As the gate was opened, it was allowed to stop at 6 inches automatically and again at 1 foot. The auto-stop function was overridden (normal procedure) with no stop being made at the 2-foot level. As the gate opening approached 2.4 feet, the gate operator felt an “unusual vibration” and he stopped the gate hoist motor. As the operator turned to check the gate, he saw the right side of the gate swing open slowly, like a door hinged on the left side and saw water pouring around both sides of the gate leaf. The time from the operator’s initial awareness of the vibration to observing gate displacement and uncontrolled flow of water was estimated to be no more than 5 seconds.

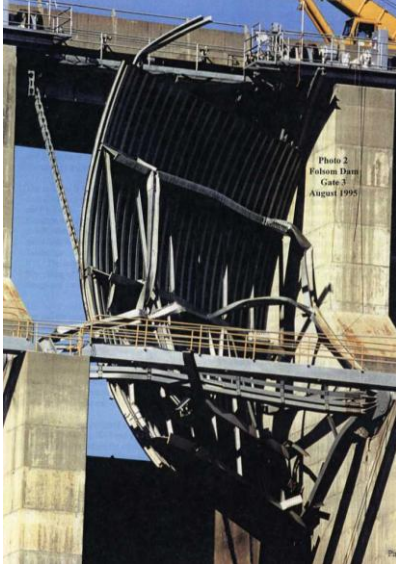


Figure VII-1-3 – Failure of Radial Gate No.3 at Folsom Dam

Nimbus Dam, the afterbay dam for Folsom, did not overtop due to the prompt action of the dam operator at Folsom Dam. He immediately informed emergency personnel about the gate failure then drove 7 miles to Nimbus Dam to open the gates to regulate the additional inflow from Folsom Dam.

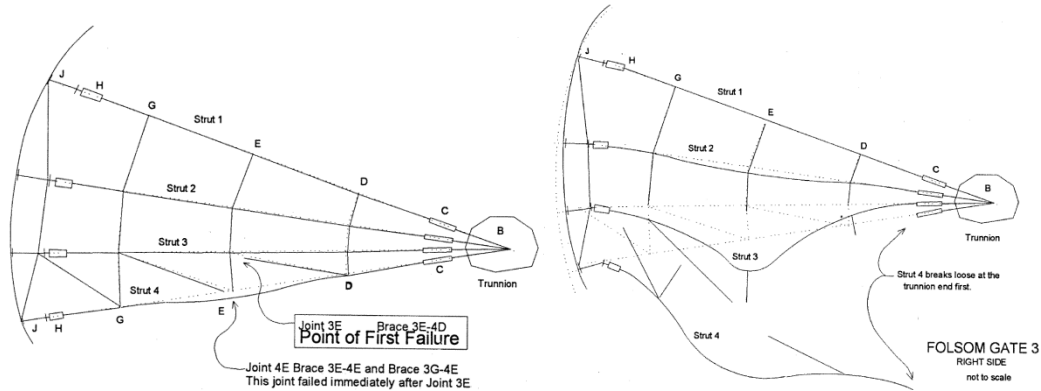
Forensic investigations

Following the failure of Gate No.3, a multi-disciplinary, multi-agency forensic team was formed to investigate and determine the cause of the failure. The team identified two main causes of the gate failure:

- Insufficient stiffness and strength in critical structural gate arm members
- Increased trunnion friction by corrosion of the steel trunnion pins

According to the forensic investigations, collapse of the gate was initiated by a failure of the bolted connection at the upper end of the diagonal strut brace nearest the trunnion in the right arm frame (see Figure **VII-1-4**). Once the initial diagonal brace failed, load was transferred to the adjacent brace connections, which failed in turn. Immediately following the brace connection failures, the lower most strut (strut No. 4) buckled downward leading to buckling of the remaining arm struts (see Figure **VII-1-4**).

More than 30 different types of tests, examinations, and analyses were performed to assist the Forensic Team in determining the cause of the gate failure. The forensic team determined that the high friction at the gate trunnion contributed to a significant increase of tension in the brace member that initially failed. According to the forensic report, the radial gates at Folsom Dam were not designed for any trunnion friction load, which was consistent with the engineering practice at the time.



Unique features of the Folsom radial gate

It appears that some features that were unique to the radial gates at Folsom Dam, could have contributed to the failure of the structure. These are:

Corrosion of trunnion pins - Corrosion of trunnion pins made of carbon steel type SAE 1045 (BH 108 min.) resulted in increased friction between pins and bronze bushings. The trunnion test data showed the friction coefficient of 0.15 for the new gate installation. The coefficient of friction was back calculated to be between 0.22 and 0.28 but could have been as high as 0.3 at the time of the gate failure. A reduced frequency of lubrication and lack of weather protection (at both ends of the trunnion pin, where gaps between the trunnion hub and the bearing housing allowed rainwater, spray, and water vapor to enter) increased the rate of corrosion over the years.

Large diameter of trunnion pins – The 32-inch outside diameter of the hollow trunnion pins (I.D, 24 inches) significantly increased the bending moment induced by the trunnion friction that transferred to the gate arm frame.

Small angle between arm members – The extremely small angle of 14 degrees between the brace member (that initially failed) and the arm struts resulted in magnified tension forces in the brace connection.

Arrangement of gate arms at the trunnion end – The "bent" type arms at the trunnion end could lead to the second order bending and torsion of the arm struts even though trunnion tie members were provided (see Figure VII-1-5).

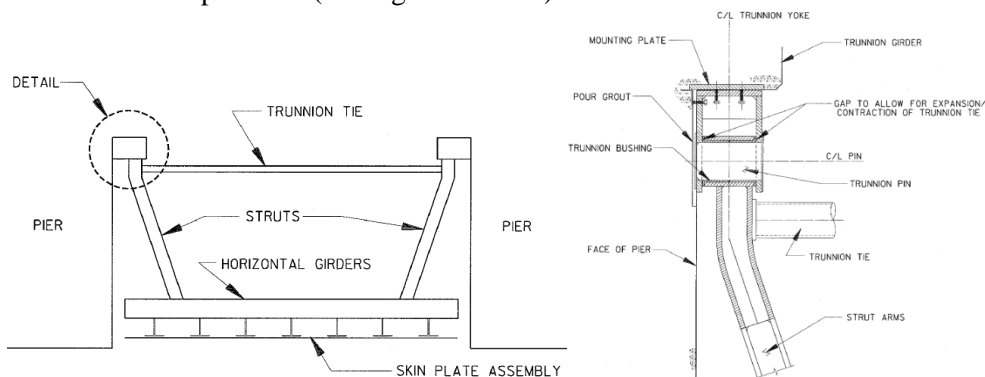


Figure VII-1-5 – Gate arm type arrangement at trunnion end used at Folsom Radial Gates (ref. USACE EM 1110-2-2702, Figure 3-5).

Strength and Stability Evaluation of Radial Gates

The intent of this section is to provide criteria for strength and stability analysis of radial gates for risk evaluation of potential gate failure. The analysis for the strength and stability should include axial, shear, and bending deformation in the structural members and their connections. In general, it is required that stability is maintained for the gate as a whole and for each component of the structure. The type of analysis used to evaluate the structural performance of the gate will be dependent of the level of risk assessment being performed. Unless the spillway gates have a simple arm frame arrangement, where hand calculations might be performed, Reclamation will perform finite element (FE) analysis when evaluating gate performance. The level of the finite element model complexity can be adjusted to the level of the analysis. For preliminary analyses, only the arm struts may be modelled. For higher level analyses, the entire gate structure would be modelled. USACE will evaluate gates through less rigorous analysis and existing information when performing Periodic Assessments or Semi-Quantitative Risk Assessments. If the gates are found to be above tolerable risk guidelines through these somewhat conservative assessments, more rigorous analysis such as FE method should be considered. When analyzing the gate structure, the following should be considered either numerically or qualitatively:

- Initial imperfections of the gate assembly – imperfections considered at the points of intersection of arm struts and their brace members
- Initial deformation of the gate arms due to the gravity load
- Stiffness reduction due to inelasticity
- Deformation of gate arms by the bending moment generated by the trunnion pin friction and deflection of the gate girders
- Defects in the gate members and their connections

In order to incorporate some of the above items, an inspection will be required to capture the current condition of the gates. The structural analysis of the gate should incorporate second-order effects ($P-\Delta$ and $P-\delta$ effects for braced gate arm struts and $P-\delta$ effects only when arm struts are unbraced). In general, the rigorous analysis method of second-order analysis is acceptable for all gate arm arrangements considering conditions of the structure geometry (listed as items a. through e. above). Alternatively, an approximate second-order analysis can be utilized by amplifying the required strength determined in a first-order analysis. The multipliers to account for $P-\Delta$ and $P-\delta$ effects, not discussed in this document, should be determined as provided in Appendix 8 of AISC 360-10.

Structural Analyses

In a current practice of the structural analysis of hydraulic gates, a finite element (FE) model of the entire gate (including skinplate, skinplate ribs, girders, arm frame, and trunnions) is typically developed. However, for a screening level stability analysis of gate arms, hand calculations together with an approximate second-order approach can be used for a simple arm frame arrangement. The stability analysis of the gate needs to consider all load combinations together with the initial imperfections of gate geometry.

Analysis Basis

In the structural based evaluation of the radial gate, a limit state approach is used to determine conditions in which the gate has reached its ultimate loading capacity (Strength Limit State). In general, limit states take the form:

Demand \leq Capacity

Required strength or demand is the internal force in a gate member derived from the structural analysis. The available strength or capacity is the predicted ultimate capacity of these members. Uncertainties in the loading and variability of material should be considered during the risk assessment through sensitivity analysis or probabilistic analysis. The interaction ratio (IR) in **equation VII-1-1** is used to assess the stability of a structural member subjected to axial compression and bi-axial bending. Instability of the member will occur in accordance to AISC when the loadings result in the interaction ratio exceeding 1.0. When evaluating stability for a risk assessment all load and resistance factors are equal to 1.0 so the actual load carrying capacity of the structure is evaluated.

$$IR = \frac{P_u}{P_n} + \frac{8}{9} \left(\frac{M_{ux}}{M_{nx}} + \frac{M_{uy}}{M_{ny}} \right) \quad \text{for } \frac{P_u}{P_n} \geq 0.2$$

Eq. VII-1-1

$$IR = \frac{P_u}{2P_n} + \left(\frac{M_{ux}}{M_{nx}} + \frac{M_{uy}}{M_{ny}} \right) \quad \text{for } \frac{P_u}{P_n} < 0.2$$

where: P_u – required axial strength

P_n – the available axial strength equals the nominal compressive strength

M_u – required flexural strength

M_n – the available flexural strength equals the nominal flexural strength

subscript x and y relating to strong and weak axis bending, respectively

Equation VII-1-1 is depicted graphically in **Figure VII-1-9**. The required strength (axial forces and moments) includes second-order effects in the interaction equation (**Eq. VII-1-1**). Second order effects are calculated in the analysis when using FE method, not in the interaction equation as it was done previously in 2014 Best Practice Manual. This is the key change in the approach implemented in the current version of the Best Practice Manual when compared with the previous editions. For less rigorous analysis, where second order effects are not quantified directly, an approximate second order analysis can be utilized by amplifying the required strength determined in a first order analysis, as described previously.

The interaction equation could also be used to determine critical trunnion pin friction coefficient for which the radial gate will lose its stability for a given hydrostatic and hoisting loads.

It should be noted that radial gates typically include bracing to reduce the unsupported length of the gate struts in weak axis bending. The analysis may indicate that a bracing member or its connection is a critical component in the stability of the gate arm, and a judgment will be needed as to the likelihood that the bracing would fail under the loading range evaluated, leading to a greater unsupported length of the gate arm struts. If a bracing member is judged likely to fail through in the structural analysis, the bracing

member should be removed from the model and the analysis rerun to evaluate the potential failure of the gate. As a result, the members that are considered as a fracture critical members (FCM) (members whose failure will lead to the failure of the whole gate structure) need to be identified in the analysis.

Serviceability Limit States

Serviceability limit states define functional requirements of the gate operation. The common serviceability limit states for radial gates are deformation and vibration. Such requirements do not impact the risk for people lives, therefore are not discussed in this section, but may result in proper functionality of the radial gates.

Stability Analysis of a Single Strut Arm

In this section, a stability analysis of a single gate strut arm is performed and a second order effect is illustrated for an axially compressed strut (**Figure VII-1-6**). First, the Euler buckling load of 130,400 lbf was determined from **equation VII-1-2** for 28-ft long, free supported at the ends, W14x48 member.

$$P_e = \frac{\pi^2 EA}{\left(\frac{KL}{r}\right)^2} \quad \text{Eq. VII-1-2}$$

where for W14x48 section $A=14.1 \text{ in}^2$, $r=1.91 \text{ in}$, $E=29,000,000 \text{ psi}$, $K=1.0$.

The result from **equation VII-1-2** corresponds well with the critical buckling load of 130,200 lbf obtained from the FE analysis for the corresponding single strut model.

Next, the single strut shown in **Figure VII-1-6** was loaded by 200 lbs/ft uniform load (bending about the major axis) and then axially compressed. The analysis results are presented in **Table VII-1-3**. As can be seen from the table, an increase of the axial force P leads to the increase of deflection and the bending moment of the strut. The results demonstrate the significance of the second-order effect in the compressed strut.

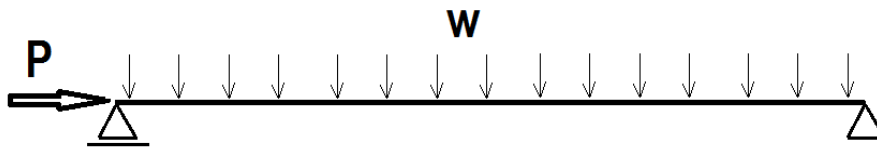


Figure VII-1-6 – Model of a single gate arm strut.

Table VII-1-3 – Illustration of second-order effects in 28-ft long arm W14x48 strut bent about strong axis with uniform load of 200 lbs/ft.

Axial Force, P	0	150 kips	300 kips	450 kips
Moment [kip-in]	235	269	313	373
Max. deflection [in]	0.196	0.223	0.259	0.308

Table **VII-1-4** presents the results of the second-order analysis of the single W14x48 strut bent about the weak axis, considering the member self-weight equivalent to the uniform load of 48 lbs/ft.

Table VII-1-4 – Results of second-order (S-O) analysis for a 28-ft long horizontal W14x48 arm strut bent about the weak axis considering self-weight of the member.

Second-order (S-O)	Axial Force, P[kips]					
	0	30	60	90	101	105
Moment [kip-in]	55.5	72.5	105	182	252	293
Max. deflection [in]	0.44	0.57	0.81	1.45	1.99	2.31
IR (Eq.VII-1-1) with S-O effect	0.05	0.30	0.56	0.86	1.00	1.07
IR (Eq.VII-1-1) without S-O effect	0.05	0.28	0.51	0.74	0.83	0.86

Results in **Table VII-1-4** show the likely failure of the strut for the interaction ratio IR equal 1.0, corresponding to the axial load of 101.0 Kips when the second-order effect is included in the analysis. Analysis of the strut without the second-order effect results in IR=0.83 for the same axial load, significantly underestimating the potential failure of the member.

Stability Analysis of Two-Strut Gate Arms

Stability analysis of a two-strut gate arm was performed for the gate model shown in **Figure VII-1-7**. The gate radius is 28-ft and both gate struts and the bracing members are made of W14x48. All members are rigid connected to each other.

The load is applied to the gate arm in stages, starting with the self-weight of the structure, and is followed by the axial compressive force P gradually applied up to 200,000 lbf. Finally, the trunnion moment is gradually applied up to 1,000,000 lbf-in. The analysis results are presented in **Table VII-1-3** and the deformation of the arm for the staged applied loads is shown in **Figure VII-1-8**.

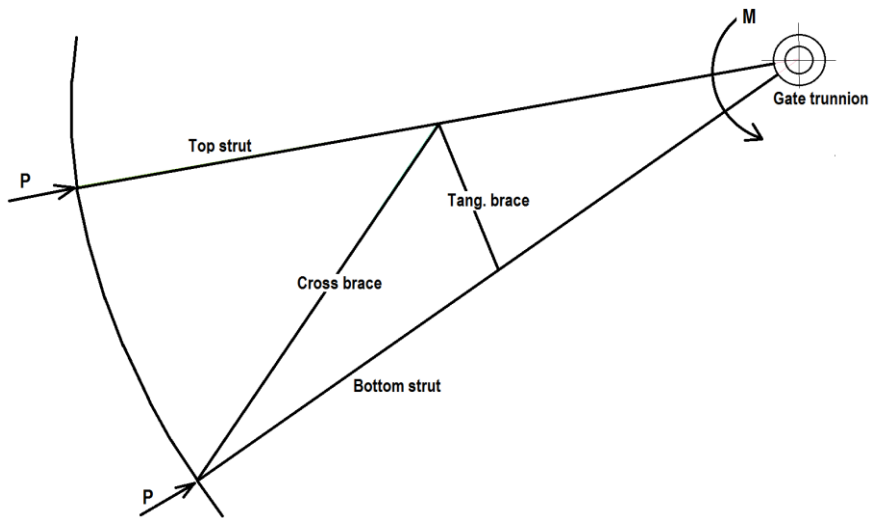


Figure VII-1-7– Model of two-strut arm for the analysis.

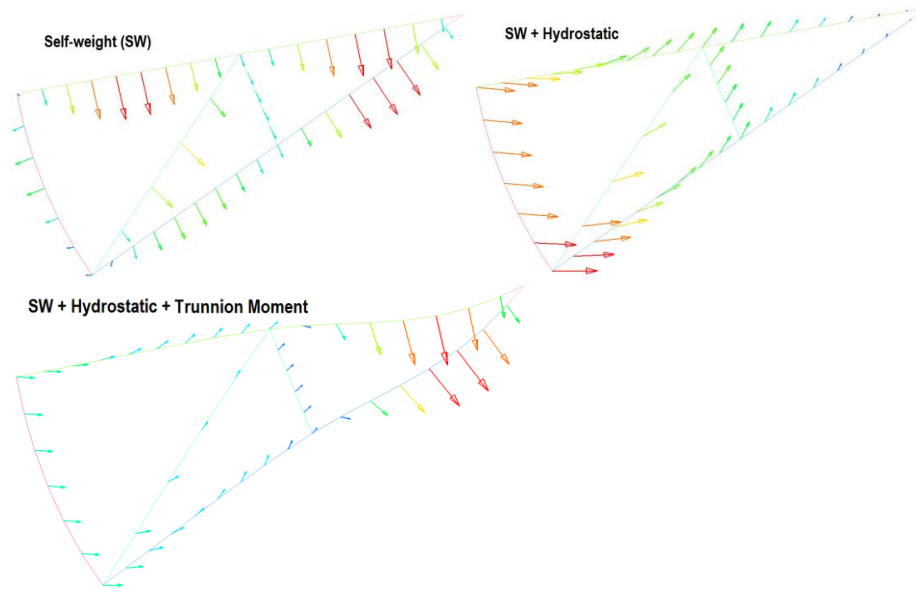


Figure VII-1-8– Deformation of the gate arms for staged load.

Figure VII-1-8 shows deformations of the gate arm for the loads applied in stages. In **Table VII-1-5** the maximum bending moment and the axial force in the struts are presented together with the interaction ratio computed based on **equation VII-1-1**. The analysis results show that higher internal forces exist in the upper strut than the lower one, even though equal axial load is applied.

For the given axial loads and the trunnion moment of 1,000,000 lbf-in the interaction ratio is equal to 0.97 and 0.88 for the upper and the lower strut, respectively. The results indicate that the gate arm has not reach its critical stage but the gate will very likely fail for the defined load conditions (per **Table VII-1-7**).

Table VII-1-5 – Results of second-order (S-O) analysis for a two-strut arm.

Max. Moment in Strut [kip-in]	Trunnion Moment, M [kip-in]					
	0	200	400	600	800	1,000
Upper strut	9.8	104	198	291	385	478
Lower strut	3.8	88.8	183	276	371	465
Axial Force in Strut [kip]						
Upper strut	201	204	207	209	212	215
Lower strut	198	196	193	191	189	186
Interaction ratio IR						
Upper strut	0.51	0.61	0.69	0.78	0.87	0.97
Lower strut	0.50	0.57	0.64	0.72	0.81	0.88

Risk Analysis

Failure of a Radial Gate under Normal Operational Conditions

The radial gate potential failure mode during normal operational conditions is broken into the following component events:

- ↳ 1. Reservoir load ranges
- ↳ 2. Gate operates
- ↳ 3. Reduction Factor due to Gate arrangement/structural conditions
- ↳ 4 Reduction Factor due to Inspections/Exercising
- ↳ 5. Bushing fails
- ↳ 6. Arm strut buckle and gate fails
- ↳ 7. Unsuccessful Intervention

The following is an example potential failure mode description for the failure of a radial gate under normal operational conditions:

Due to the reduced frequency of lubricating the radial gate trunnion externally lubricated bushings, trunnion friction increases over time. The friction reaches a level where the bending stresses in the right bottom arm strut combined with the axial stresses from a full reservoir causes the lower right arm strut to buckle. This causes a rapid progressive failure of the other two right arm struts, resulting in a release of the reservoir through the partially restricted opening.

Event Tree

An example event tree for the radial gate failure mode is shown in Figure VII-1-10. For this potential failure mode, the probability of the reservoir loading may be high, especially for a spillway that operates frequently. There is really only one conditional failure probability (buckling of the gate arms – which is considered under original design conditions and a failed bushing condition). The combination of a high loading probability and one conditional failure probability event may make it difficult to estimate risks below guidelines for well-designed gates. There is also the historical evidence that radial gates perform very well under normal operational conditions, with the only failure within the Reclamation/USACE inventory being the Folsom Dam gate. In order to address this situation, two reduction factors have been added to the event tree that address the arrangement/condition of the radial gates and the frequency of inspections/exercising of the gates. These factors can reduce the overall failure probability if favorable conditions exist and are justified because they reduce uncertainty and improve the confidence in the risk estimates.

Reservoir Load Ranges - The first node represents the reservoir load range and provides the load probability. Some thought needs to go into selecting reservoir ranges and the associated probabilities. One case would involve the threshold where the first gate operation would take place to release flood inflows, and the flood range probability would be associated with the flood frequency for this case up to the flood at which the next gate would be opened. A second gate discharge may be needed during a large flood, to prevent the reservoir water surface from rising and overtopping the dam. Then,

similarly, as each additional gate is opened for flood operations, the flood range and associated probability associated with that level of flooding is included. Additional discussion of multiple gate failures during a flood is provided in the Consequences discussion that follows.

If there is the possibility that testing of the gates could cause a gate failure, then the time of year the gates are typically tested is determined, and the likely reservoir ranges at the time of testing are used. If a spillway gate failed due to trunnion pin friction during testing, it is expected that additional gates would not be opened and that the failure would be limited to one gate. Historical reservoir elevation data can be used to generate the probability of the reservoir being within the chosen reservoir ranges, as described in the section on Reservoir Level Exceedance Curves.

Gates Operate – This event considers whether spillway gates will be opened for a given reservoir range. This event can be deleted or set to 1.0 if the gates are operated frequently or if there are other reasons where this event will not make a difference (i.e., the reservoir is almost always full and the gates are exercised annually).

Reduction Factor due to Gate Arrangement/Structural Conditions - The third node in the event tree is a reduction factor relates to the gate arrangement and the structural conditions. A factor between 0.1 (for very favorable conditions) and 1.0 (for adverse conditions) can be used and the risk team should evaluate the conditions and determine a factor to be used.

Some of the conditions that could influence the team in the selection of the reduction factor are included in **Table VII-1-6** below. The extent that a condition applies and the number of conditions that are applicable should be considered when selecting the appropriate value.

Table VII-1-6 Reduction Factor Considerations Related to Gate Arrangement/Condition	
Condition	Considerations
Age of Gate and Frequency of Gate Operations	Older gates (more than 50 years old) will be more vulnerable to failure given: <ul style="list-style-type: none"> • fatigue in the gate structure members during operational life of the structure and • potential for increased trunnion pin friction over time.
Complexity of the Gate Arm Frame Assembly	Gates with more members may be more vulnerable to failure due to an increased number of connections and the increased potential for one or more of the critical members to have defects which could lead to the failure of the whole gate structure.
Fracture Critical Members	Fracture critical members are defined as members whose failure would lead to a catastrophic failure of the gate. Gates with multiple fracture critical members are more vulnerable to catastrophic failure.

Fatigue of the Gate Members	Cyclic loading of the gates members may lead to fatigue of the fracture critical members or their connections during operational life of the gate. Gates with multiple fracture critical members and with longer operational life and higher operational frequency, or that have a history of vibration during operation are more vulnerable to failure of their members.
Welded Connections	Welded connections can be more vulnerable to undetected cracking, during operational life of the gate.
Age of Coatings	Coatings that are older are more likely to have localized failures that could lead to corrosion and loss of material.

Reduction Factor due to Inspections/Maintenance/Exercising of Gates - The fourth node allows for further risk reduction to the failure probability estimate, based on regular gate inspections, maintenance, and regular exercising of the gates. The expectation is that regular inspections and exercising of the gate will identify potential issues in their early stages and that maintenance measures will be taken to correct any developing issues. A reduction factor of between 0.1 and 1.0 should be selected by the risk team for this node. Ideally gates should be exercised annually and thoroughly inspected every three years. If this is the case, and no adverse conditions are found, the team should consider a value of 0.1. If the gates are not exercised (either as a matter of O&M practice or as part of flood operations) or inspected, a value of 1.0 should be considered. The team should evaluate conditions between these two extremes and select an appropriate factor, properly documenting the factors that led to the estimate.

Bushing Fails – This event requires a probability distribution between two conditions – the bushings are intact and lubrication is regularly provided for externally lubricated bushings and a failed bushing condition, where a portion of the bushing self-lubricating liner has been damaged or lubrication for an externally lubricated bushing is non-existent or ineffective. The risk team should decide on how to distribute a probability of 1.0 between the two based on conditions at the site. If the gates are well maintained and there is no evidence of a failed bushing, the probability of the failed condition should typically be 0.05 or less. If trunnion friction coefficients greater than the design values are expected, higher probabilities may be appropriate.

Arm Struts Buckle and Gate Fails - The sixth node is the conditional failure probability that is based on the calculated interaction ratios of the gate arms. Two conditions will need to be estimated based on the split in the previous node – a non-failed bushing condition (where the original design intent is met) and a failed bushing condition. Ideally two analyses of the gate will be available that reflect the two different bushing conditions and the appropriate friction coefficients. If the gates are loaded to the point of overstressing the radial gate arms, the gate arms can buckle and fail, leading to gate collapse and reservoir release without additional steps in the event sequence.

With the interaction ratio curves as a guide (see **Figure VII-1-9** and **Table VII-1-7**), estimates can be made for the probability of a single gate failing under the conditions analyzed. These estimates are made based on the highest interaction ratio calculated for the gate arms from the structural analyses.

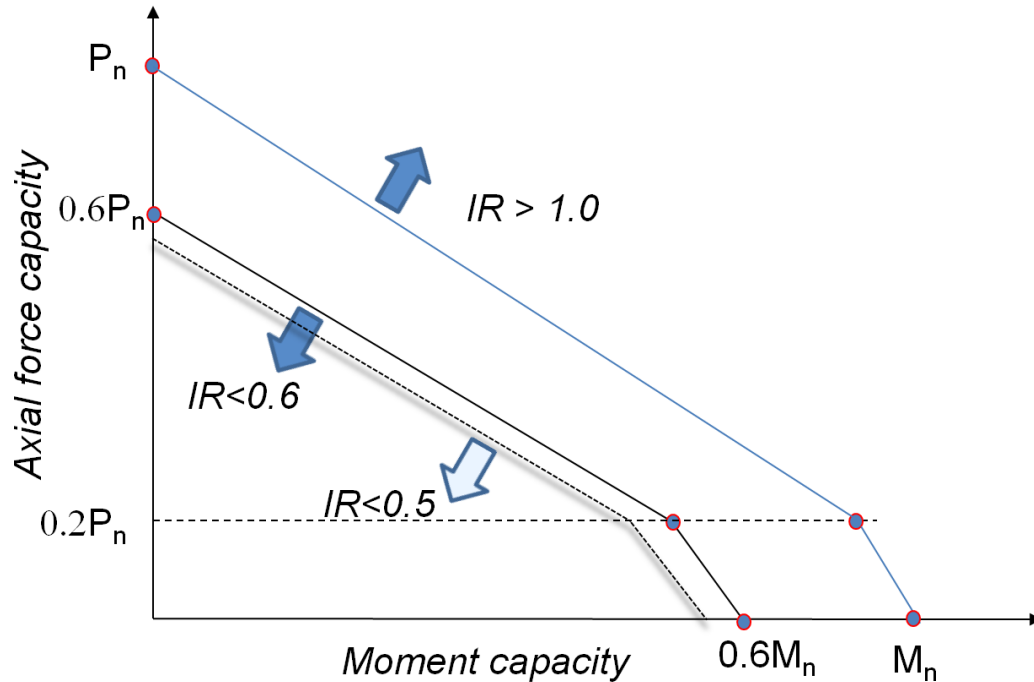


Figure VII-1-9 – Illustration of interaction ratios for radial gate.

Table VII-1-7 - Gate Failure Response Curve

Interaction Ratio	Probability of Failure (1 gate)
< 0.5	0.0001
0.5 to 0.6	0.0001 to 0.001
0.6 to 0.7	0.001 to 0.01
0.7 to 0.8	0.01 to 0.1
0.8 to 0.9	0.1 to 0.9
0.9 to 1.0	0.9 to 0.99
> 1.0	0.9 to 0.999

Intervention Unsuccessful - The fifth node allows for termination of this potential failure mode if intervention can succeed in stopping or significantly reducing flow in a reasonable period of time (before significant downstream consequences are incurred). In most cases, it will be likely to virtually certain that intervention will be unsuccessful. In order to be successful there will need to be an upstream gate or a bulkhead (either of which would have to be able to be installed under unbalanced conditions) that could be closed to stop flow through the failed gate.

Risk estimates made using the above approach seem to be consistent with the historic failure rate for Reclamation spillway radial gates. Reclamation has 314 spillway radial gates in its inventory. There is a total of about 20,000 gate years of operation for these

gates (as of 2015). The only failure due to trunnion pin friction (or any loading condition for that matter) was the Folsom Dam gate that failed in 1995. The base failure rate is 1/20,000 or 5×10^{-5} . The results obtained by using the event tree proposed in this section seem consistent with this base failure rate.

If existing gates have interaction ratios for all arm struts below 0.6, there is only a small failure probability for a failed bushing and the gates are exercised annually and inspected thoroughly at least every three years, the annualized failure probability should be less than 1×10^{-5} and possibly lower than 1×10^{-6} . If the critical interaction ratio is between 0.6 and 0.7, there is only a small chance of a failed bushing, and the reduction factors for gate arrangement/condition and gate inspection/exercising are both 0.3 the annualized failure probability can be as high as 9×10^{-5} to 9×10^{-4} .

Given the judgments that are needed to evaluate this potential failure mode, judgmental probabilities are typically used to assign likelihoods to each node as described in the section on Subjective Probability and Expert Elicitation. Refer also to the section on Event Trees for other event tree considerations.

Multiple Spillway Gates

For spillways with multiple radial gates, failure during gate operation is most likely to result in only one gate failing, since the gates are typically not all operated simultaneously, and failure of a gate would likely result in an evaluation, and a reluctance to operate the other gates. However, there is more of a chance that one of the gates will fail if multiple gates are present, and failure of one large gate could exceed the safe channel capacity or surprise downstream recreationists with life-threatening flows.

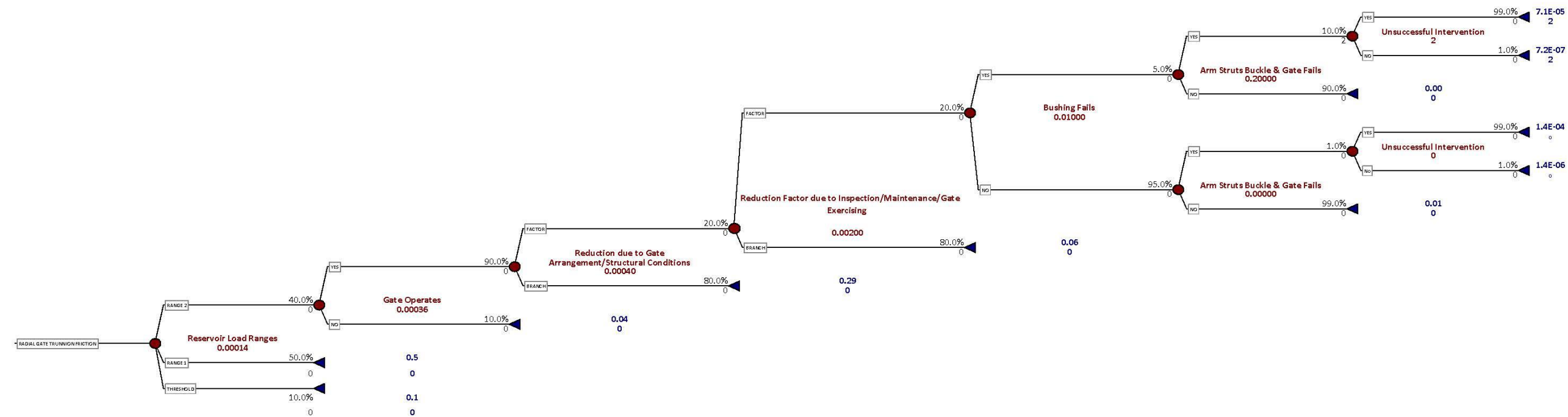


Figure VII-1-10 – Example Event Tree for Radial Gate Potential Failure Mode

Consequences

Consequences are a function of the reservoir level at the time of failure (which determines the breach outflow). Loss of life can be estimated from these breach flows (typically resulting from the failure of one spillway gate) and the estimated population at risk that would be exposed to the breach outflows using the procedures outlined in the section on Consequences of Dam Failure.

When spillway gates are operated, they typically are opened slowly to ramp up the flows. Failure of a spillway gate during operation would likely result in a sudden large increase in spillway flows. While the flows may be within the “safe channel capacity,” they may be large enough to endanger recreationists, especially during sunny day testing of the gates, where there is not an anticipation of spillway releases or above normal streamflows.

If a spillway with multiple gates is being operated during flood conditions and the spillway capacity provided by more than one gate is needed to pass the flood, it may be possible that multiple gates would fail due to gate operation. The scenario would be that one spillway gate is initially opened to pass flood inflows and the gate fails suddenly. The increased discharge through the failed gate bay would likely be enough to match incoming flows for a while. At some point, the inflows would increase to the level that discharge from a second spillway gate would be needed to prevent the reservoir from rising to the level that dam overtopping would be possible. The decision would likely be made to open the second gate, recognizing that it too may fail. Mitigating this situation is the likelihood that the initial gate failure would evacuate the channel of the recreation populations and the fact that there would some delay in between the first gate failure and the time when a second gate would need to be opened. This would allow for downstream warning and evacuation. If conditions are such that incremental loss of life would occur with successive failure of spillway gates, and if the probability of a flood that would require more spillway capacity than that provided by a single gate is large enough, this scenario may need to be considered.

Accounting for Uncertainty

Typically, the reservoir elevation exceedance probabilities are taken directly from the historical reservoir operations data, directly, which do not account for uncertainty. Uncertainty in the failure probability and consequences are accounted for by entering the estimates as distributions (as describe above) rather than single point values. A “Monte-Carlo” simulation is then run to display the uncertainty in the estimates, as described in the section on Combining and Portraying Risks.

The risk team can also evaluate uncertainty in the performance of the gate by performing sensitivity analysis of the interaction ratios by varying trunnion friction coefficient. If friction coefficients above the design value are expected but exact values are unknown, sensitivity analysis can be used to inform the team on ranges of loading that could potentially be of concern. Using historical performance and loading of the gate and the results of the sensitivity analysis, upper and lower bounds of trunnion friction could be

calculated. This information could then be used to inform the team when selecting probabilities and reduction factors for the event tree.

Considerations for Comprehensive Review/Periodic Assessment

The complete analysis as described in this section is likely too time consuming to be performed during a Comprehensive Review (CR) as specified in Reclamation methodology or a Periodic Assessment or Semi-Quantitative Risk Assessment (SQRA) for USACE dams. Therefore, simplifications must be made. Typically, only the critical load for the initial gate operation or testing is considered. Uncertainty is typically taken as plus or minus an order of magnitude. If results of finite element gate analyses are available, they can be used to help define the load and reservoir ranges to be considered. If no gate analyses are available, searching for results related to similar gates should be undertaken or a simple hand calculations could be performed if the gate arrangement is not complex. The USACE Risk Management Center has a spreadsheet based analysis tool that can be used to evaluate common gate configurations for a trunnion friction failure.

Exercise

Consider a spillway with two radial gates, each 34.5 feet high by 51 feet wide. The reservoir is at the normal pool elevation (3 feet below the top of the gates in the closed position) at least two months of every year. Structural analyses of the gates have been performed with the reservoir at the normal pool elevation and assuming a trunnion friction coefficient of 0.1 (based on the manufacturer's recommended value for the bushings). The critical interaction ratio (IR) for this condition is 0.6. If the bushings were to fail, the friction coefficient could increase to 0.3 (assume a 1 percent change that this happens). With the increased friction, the IR will increase to 0.8. The trunnion pins have a self-lubricating bushing and the gates are exercised annually and thoroughly inspected every three years. Assume that there are no adverse factors listed in **Table VII-1-5** that apply to the gates and that unsuccessful intervention in the event of gate failure will be very likely. Estimate the expected annual failure probability for gate failure during the annual exercising of the gates, which typically occurs when the reservoir is full.

References

American Institute of Steel Construction, Specification for Structural Steel Buildings, AISC Standard 360-10, June 22, 2011.

USACE ETL 1110-2-584 – Design of Hydraulic Steel Structures, June 2014.